Superconducting Power Cables in the RHIC Project[1]

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Abstract

The RHIC Project, now in construction at Brookhaven National Laboratory, will use a superconducting power cable, known as the Cold Crossing Bus, to make most of the connections between the power supplies and their magnet loads. Within a single one inch diameter cable, circuits summing up to over 27,000 amps can be carried. Yet, the cable is flexible enough to be installed in a four inch helium transport pipe with a nine inch bend radius. In addition to connecting to power supplies, it will be used to cross the intersection regions without going through the experimental area and will be used to bypass warm sections of the beam tube. Use of this cable will result in cost savings in cable material and installation costs, as well as lower operational costs due to reduced power losses as compared to warm cable.

1. INTRODUCTION

RHIC consists of two rings that cross each other in six equally spaced locations in a 3.8 km long tunnel. Each of these six crossing points is a possible location for experiments. At some of these points, there are large buildings to house the experimental equipment.

Although there are some small rooms along the length of this tunnel, most of the power supplies must be outside, in equipment service buildings. These service buildings also house the cryogenic valve boxes, which, in addition to being too large to put in the tunnel, also need to be easily accessed. Thus, at each crossing point, helium will be brought out of the ring, and up into the building where the power supplies are located. Superconducting cables, called Cold Crossing Bus (CCB), will be placed in these helium transport lines, and the cold to warm transition for the power leads are to be made at the valve boxes in the service buildings.

2. POWER SUPPLY REQUIREMENTS

There are three general categories of power supplies at RHIC, and the CCB was designed with this in mind.

2.1. Main Power Supplies

The main dipoles and main quadrupoles will both nominally require 5,000 amps, but they are separate isolated circuits. Each circuit is driven by a single power supply. The main dipole current serves as a baseline to the insertion dipoles, and the main quadrupole current is the baseline for the insertion quadrupoles. The last dipole in the string, DX, is an insertion dipole rated at 6,300 amps. This sets the design current for the CCB large conductors.

The main quadrupoles are electrically grouped into horizontal and vertical quads, and provisions are made to offset the two types by up to 450 amps.

2.2. Insertion Magnets

The field in the nine quadrupole magnets on either side of each crossing point in each ring are used to tune the beams where they intersect. By adjusting the currents around a baseline value, the magnitudes are kept low. But, the quantities are high: 168 power supplies are required at 150 amps, and another 46 units are needed in the 450 to 600 amp range.

The insertion dipoles also have their currents adjusted around a baseline value, but require bypass currents of up to 1600 amps.

2.3. Correction Magnets

The correction power supplies range in value from 25 to 100 amps, and are all located in the small rooms within the tunnel. The current is carried over warm conductors to the corrector packages which have individual cold to warm power leads. The CCB is not used for powering correction magnets.

3. CCB DESIGN

3.1. Basic Design Considerations

The power supplies as well as the physical construction of the RHIC collider tunnel are based on the use of the CCB. For this reason a great deal of design margin was required to ensure confidence. The superconductor components used to make up the CCB have been in use in other areas of the RHIC project, and their performance is well known.

Mechanically, the cable needed to be flexible enough to go through 100 feet of four inch pipe, including a single nine inch bend radius elbow. Electrically, the cable had to have the capacity to carry the shunting supplies as well as the main supplies. This allowed all of the currents in a single cable to sum to zero. And, the cable needed enough copper backing up the superconductor to absorb the energy that would be delivered for the time it would take the quench protection circuitry to absorb the energy stored in

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the main magnets.

Conventional copper wires were also added to the CCB assembly to detect any quenches in the cable itself.

As an added bonus, money could be saved by using existing inventories of superconductor strand and cables.

3.2. CCB Conductors

The cross section view of the CCB is shown in Figure 1.

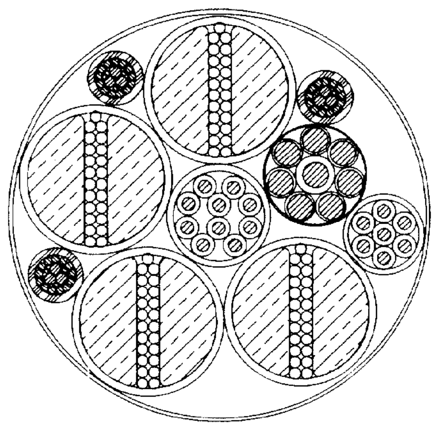

Figure 1. Cold Crossing Bus

There are four 6,300 amp rated conductors. At their core is a 23 strand cable that uses 0.0268 inch superconductor strand. This is the same cable that was used to make CBA magnets, and will be used to interconnect magnets in RHIC. The cable has a critical current rating of 11,000 amps in zero field, which is about what they see, as the currents in the CCB will sum to zero. To increase the quench rating, 30,400 circular mils of copper is added on either side. Keeping the flexibility requirements in mind, this was accomplished with 1,218 strands of #36 AWG wire. These CCB component cables are used for all magnet loads in the 600 amp to 6,300 amp range.

For magnet loads of 450 amps, a cable with three strands of superconductor is used with an 5,729 circular mils of copper added. The three strands gives the cable a critical current of over 1,200 amps. This cable is called a "test cable," because it is used to induce a quadrupole component in RHIC dipoles during magnetic testing.

The last category of superconductor is for the 150 amp loads. In this application, three strands of superconductor is again used, but due to the low currents, no additional copper is needed. These conductors are bundled into a cable of eight wires.

Finally, there are seventeen voltage tap wires, grouped as one bundle of ten and one bundle of seven. This provides a way to measure the voltage across each of the superconducting cables.

3.3. Insulating Materials

The primary insulating material of the component cables of the CCB is Tefzel. This provides isolation of 5,000 volts between the conductors. Kapton and mylar tape is also used in some of the manufacturing steps.

The outer jacket is woven over a Kapton wrap using Nomex. The jacket is not a primary insulating layer, but is just used to hold the component cables together. The main reason for using a woven outer jacket is that it is considerably more flexible than if Tefzel was used.

When the assembly is completed, the entire cable has a diameter of just under one inch.

3.3. Miits Rating

Understanding the physical construction of the CCB permits a closer look at the quench ratings of its component cables. If a superconductor cable were to change state to a normal conductor, called quenching, the resistance of that superconductor rises dramatically. When this happens, the current flows through the copper surrounding the superconductor. The amount of energy that can be absorbed by the mass of the copper without exceeding a temperature at which the insulation can safely operate is called the Miits rating. This rating, which derives its name from Million i squared t, makes it easy to calculate how quickly the current must decay once a quench is detected. The Mitts ratings for the CCB components are given in Table 1.

Conductor Rating, amps	Miits Rating
6,300	204.00
450	1.50
150	0.11

Table 1. Miits Ratings

As an example, if there is a quench in a conductor supplying the main dipole string, the RHIC quench protection circuits will cause the current to decay exponentially with a four second time constant. The energy in that current waveform, out to infinity, is the same as contained in a rectangular pulse of two seconds. At 6,300 amps peak, the required Miits rating is:

$$Miits = (6300\ amps)^2\ (2\ secs.)\ (10^{-6}) = 79.4 \qquad (1)$$

This is much lower than the design limit of 204.0 as listed in Table 1. The extra margin provides for quench detection time, and for safe operation even if some of the quench protection switches fail.

3.4. Cable Forces

The most significant mechanical forces will be between the large conductors. The peak tension in the binding jacket for a current of 6,500 amps is 7.88 pounds per inch.

3.5. Differential Expansion

The difference in expansion between the stainless steel pipe and the CCB will be within ± 0.5 inches per 100 feet. This difference will be taken up by slack in the oversized pipe, and in the pull boxes.

4. USING THE CCB

4.1. Service Buildings

The primary use for the CCB is transporting the power from the service buildings down to the tunnel. Used this way, there will be two CCB cables in each vacuum jacketed piping going down to the tunnel. One is primarily for dipoles and the other for quadrupoles. Physically they are the same, except the quadrupole CCB requires three test cables, vs. two in the dipole CCB.

The savings in using the CCB in this way is dramatic. A single 6,300 amp conductor replaces twelve 535 kcmil warm conductors, along with the associated cable trays and supports. While not all the 6,300 amp conductors are run at that level, there are eight such conductors between the two CCB cables. In addition to the cost savings in materials and installation, the CCB does not require large openings in the service buildings, and more importantly, in the tunnel that warm cables would need. All that is needed with the CCB is a two foot by six foot opening, of which a two by two foot portion is used for all warm signal cables, and a two by four foot portion that would have been needed by the cryogenic system even without the CCB.

In addition to the construction savings, there are considerable power savings. With a superconducting load, the power lost in conventional cables would have been a significant portion of the load. Using the CCB with normal running period, will result in a savings of over 6,000 MW-hrs of power each year.

4.2. Other CCB Applications

The CCB is also used internal to the tunnel where warm sections must be bridged. Here, as with the service buildings, the CCB travels along with the helium flow. There are three types of locations where the CCB bridges gaps: where magnets Q3 and Q4 are separated by a warm section of beam tube of about 120 feet, where the injection magnets enter the main rings, and where two dipoles closest to the crossing point, D0 and DX are separated by a warm section.

5. CURRENT STATUS

5.1. Manufacturing

The cable is presently being manufactured at New England Electric Wire Corp. Approximately 9,000 of the required 28,000 feet have already been fabricated. The entire quantity will be completed by early 1995.

5.2. Installation and Testing

The CCB will be installed at the same time that the vacuum jacketed piping for the helium transport is installed. This is scheduled to start early in 1995.

The testing philosophy used for the CCB is very similar to that used in the manufacturing of superconducting magnets. Careful attention to, and testing of the components gives a high confidence level for the finished assembly. Using the 6,300 amp conductor as an example, first the superconducting strand is tested, both at warm and cryogenic temperatures. Then it is formed into the 23 strand cable that is the core of the 6,300 amp cable. But, before the 23 strand cable is used for the conductor, a short piece is sent to BNL for cryogenic testing. After those tests, the manufacturing of that component cable can continue.

The CCB will have its first test as a completed assembly during the first sextant test at RHIC. This is the only way to get complete data on its performance. This test is scheduled for the fall of 1996. At that time, one sextant of both main dipoles and main quadrupoles will be powered, and the string can be ramped up and down at full current.

6. ACKNOWLEDGEMENT

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